

WAVELET-BASED FILTERING FOR THE CLINICAL EVALUATION OF ATRIAL FIBRILLATION

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Abstract - This paper describes the work in progress to develop a new ECG signal filtering technique to aid the clinical analysis of atrial fibrillation. The method separates the wavelet transform modulus maxima corresponding to the signal scalogram into a number of components. These groups of maxima lines are then used to reconstruct separate signals representing each of the features, including atrial fibrillation.

Keywords - Atrial Fibrillation, wavelet transform modulus maxima.

I. INTRODUCTION

Atrial fibrillation (AF) is common, with a prevalence of 0.5% in the adult population, rising to 10% or more in those over 75 years [1]. It is associated with a 5-6 fold increase in the incidence of stroke. Restoration of sinus rhythm with DC cardioversion (i.e. transthoracic electrical countershock) improves symptoms, cardiac output, exercise tolerance and reduces the risk of stroke. Although cardioversion is initially successful in up to 90 percent of selected patients, the recurrence rate can be as high as 60 percent. Several clinical variables are associated with an increased risk of recurrence – mitral valve disease, hypertension and left ventricular impairment. Even accounting for these variables in the selection of patients, the recurrence rate can remain high. At the electrophysiological level several factors may alter the propensity to recurrence, and these variables are not readily identified using the surface ECG. This includes chronic myocardial substrates (e.g. atrial infarction), atrial electrical remodelling (e.g. local resetting of the atrial refractory period) and atrial ectopy. In electrophysiological studies differing degrees of disorganisation of atrial activity may be seen during AF, with zones of disorganised activity accompanying regions of relatively regular atrial activity [2,3]. This reflects the heterogeneity of the condition, first elucidated by detailed multi-electrode mapping of the atria in human and animal models. These studies show that macro re-entry circuits involve both atria, with right atrial circuits occurring at the right atrial appendage, around the superior vena cava, and at the fossa ovalis. Left atrial circuits are more complex and involve the pulmonary vein orifices. The degree of disorganisation of activity within the atria may reflect the propensity to maintain order after cardioversion, and the presence of both unstable right and left atrial circuits may mitigate against sinus rhythm [4]. The wavelength of each re-entry circuit (determined by its conduction velocity and refractory period) determines circuit size; larger circuits occur with longer wavelengths. The minimum number of

circuits required to maintain AF is thought to be six [5]. Thus, the presence of multiple short wavelength (high frequency), unstable circuits within the atria lends itself to maintenance of AF. To date, it has proven difficult to determine the electrophysiological status of the atria with non-invasive methods. Although non-linear dynamic techniques ('chaos' analysis) have previously been used to examine the AF waveform, the relationship between parameters derived from non-linear dynamics and measured electrophysiological properties of atrial activity (and clinical outcome) are not clear [6,7].

II. METHODOLOGY

The wavelet transform is a valuable signal analysis tool that can provide spectral and temporal information from complex signals, including ECGs. It overcomes some of the limitations of the more widely used Fourier transform, which only contains globally averaged information, and has the potential to lose specific features within the signal. Recently, wavelet analysis has been applied to biomedical data including electroencephalogram, electromyogram, acoustic signals and the ECG [8-12]. Wavelet based studies of ECG signals have either examined heart rate variability, or have classified ECG waveforms. Our group have focussed on the analysis of complex waveforms during both ventricular fibrillation (VF) [13,14] and AF (as well as other engineering signals [15-17]). Our pilot studies of AF signals have used modulus maxima thresholding techniques to differentiate the underlying fibrillation waveform from QRS complexes and T waves.

For complete analysis of a response signal the frequency make up and temporal location of these components need to be deduced. As a result of the infinite extent of the Fourier integral, analysis is time averaged. This renders feature location complex, even for stationary signals. This limitation can be partly overcome by introducing a sliding time window, which localises the analysis in time. This local or short time Fourier transform provides a degree of temporal resolution by highlighting changes in spectral response with respect to time. However, this method is always a compromise between temporal and frequency resolution (higher frequency resolution means lower temporal resolution, and vice versa). The nature of the wavelet transform is such that it is well suited to analysis of signals in which a more precise time resolution is required for higher frequencies than for lower ones; i.e. the wavelet transform is suitable for locating discontinuities or singularities, in which

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high frequency components dominate. It effectively zooms in on the temporal signal when analysing higher frequencies, providing higher resolution where necessary. The wavelet transform of a continuous real-valued time signal, $f(t)$, with respect to the real valued wavelet function, g , is defined as

$$T(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} y^* \left(\frac{t-b}{a} \right) f(t) dt \quad (1)$$

where $y^*((t-b)/a)$ is the complex conjugate of the analysing wavelet used in the convolution and, in this application, $f(t)$ is the ECG signal exhibiting AF. The wavelet transform can therefore be thought of as the cross correlation of the analysed signal with a wavelet function that has been translated by a value b and dilated by a factor a . These values are often referred to as the location and dilation parameters respectively. The wavelet transform can be considered a ‘mathematical microscope’ where a^{-1} and b correspond to the magnification and location respectively.

Contemporary literature suggests two methods of wavelet analysis using either *discrete* or *continuous* transforms. The *discrete* wavelet transform necessitates the use of orthonormal wavelets, and dilation levels are set in the form of ‘octaves’ (integer powers of two). This provides a rapid method of signal decomposition, and guarantees energy conservation and exact signal reconstruction. However, the discrete transform is limited by loss of frequency resolution due to the incremental doubling of the level associated frequencies. Conversely, the *continuous* wavelet transform does provide high resolution. Thus, proper use of wavelet analysis demands identification of the correct wavelet and transform type for the given application. Our group have recently employed two types of wavelets for ECG signal analysis: the 2nd derivative of a Gaussian function (the ‘Mexican hat’), and the complex Morlet wavelet. The former has temporal compactness, useful for examining location specific features in the signal. The latter is more compact in the frequency domain and allows both amplitude and phase of the signal features to be probed simultaneously.

The *modulus maxima* technique allows salient information in the continuous wavelet transform scalogram to be represented in a compact form. This method reduces the topography of the scalogram surface to a series of ridges, reducing the data required to represent the signal. The modulus maxima obtained from a bandlimited signal, with a wavelet of finite compact support in the frequency domain, defines a complete and stable signal representation applicable to a wide range of signal types. Modulus maxima thresholding algorithms have been used in two recent studies that applied wavelet analysis to ECGs to determine heart rate variability. An algorithm has been developed by Li and colleagues to detect the characteristic points of ECG signals [18]. This algorithm can distinguish the QRS complex from P and T waves, noise, baseline drift and signal artifacts. Another group has described a wavelet-based QRS complex detector that utilises a modulus maxima algorithm to detect the exact location of the R-wave in time [19]. The methods simply use the maxima

to locate features in the signal. The technique we propose partitions the maxima lines into three groups: one corresponding to the AF fluctuations in the ECG, a second to the QRS complex and T wave, and a third to the underlying noise. These maxima can then be used to reconstruct a set of partitioned signals.

III. RESULTS [1]

Figure 1 shows a 6.82 second segment of ECG exhibiting AF collected from a patient undergoing elective DC cardioversion at the Royal Infirmary of Edinburgh. Figure 2 contains the wavelet transform energy density plot (scalogram) corresponding to the signal of figure 1. The high energy spiking corresponding to both the QRS complexes and T waves are easily seen in the scalogram. Regions of signal where there is a long R-R interval are particularly amenable to the wavelet transform modulus maxima filtering method enabling it to pick out multiple AF oscillations. One of these regions is indicated by a black arrow in the scalogram plot. A horizontal band at 50Hz is also evident in the plot corresponding to mains interference of the signal (also indicated by a black arrow on the left hand of the plot). The plots in figure 3 contain the partitioned signals. The middle of these plots contains the partitioned AF signal. We can see that the partitioned AF signal contains no trace of either the QRS complex or T wave. However, the method at present removes all signal in the region of these two features. This leaves a large proportion of the filtered AF signal equal to zero.

Fourier and wavelet frequency spectral analysis has been performed of the AF partitioned signals (not shown). The Fourier spectra indicates a dominant spectral peak at around 6-7Hz. However, the intermittent nature of the AF signal causes a spectral broadening around this frequency in the Fourier domain. On the other hand, the wavelet spectra corresponding to the filtered AF trace are, by their nature, much smoother and exhibit peak spectral frequencies within the same region as the Fourier spectra (6-7Hz).

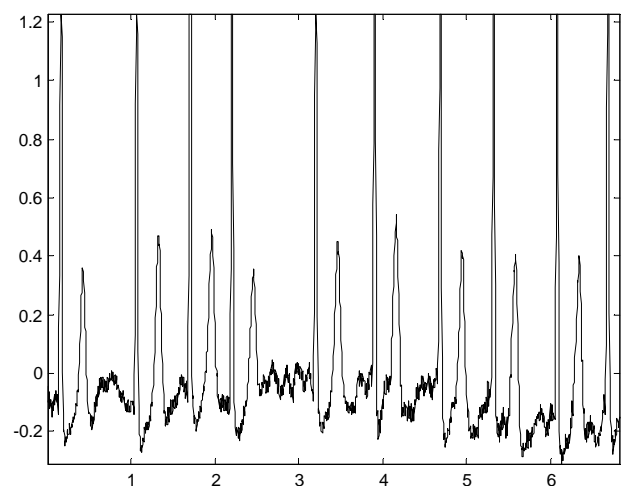


Fig. 1. 6.82 Second Segment of ECG Exhibiting AF

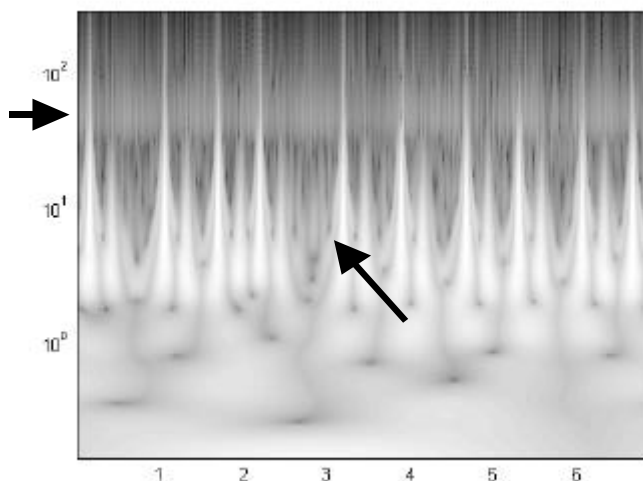


Fig. 2: Scalogram Corresponding to Signal in Figure 1.
(The highest energies in correspond to white and the lowest energies to black in the grey scale plot.)

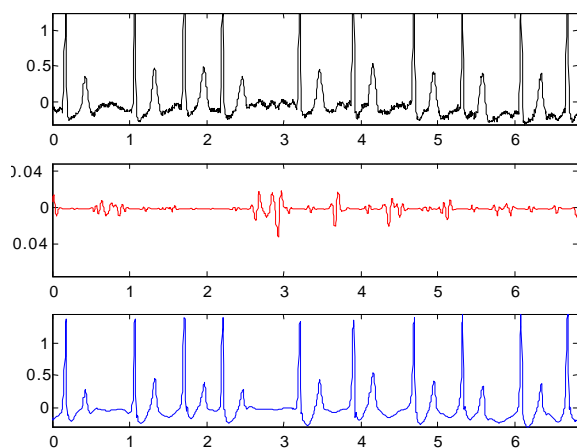


Fig. 3: Original ECG (Top) with AF filtered signal (Middle) and QRS / T filtered signal (Bottom)

IV. DISCUSSION

AF is a common arrhythmia that is associated with significant morbidity. To date it has proven difficult to study complex atrial activity in real time using non-invasive methods, to identify electrophysiological properties that determine maintenance of AF. In the clinical setting cardioversion helps restore atrial electrical and mechanical function in a proportion of patients, but the long-term success of cardioversion is often disappointing. Patient selection can be improved by applying clinical and echocardiographic screening criteria, but further discrimination could be

afforded if the electrophysiological status of the atria could be assessed prior to treatment. It is probable that patients who exhibit least disorder of atrial depolarisation (or localised ordered activity) are more likely to remain in sinus rhythm.

V. CONCLUSION

Our pilot data suggest that wavelet analysis may provide a useful non-invasive marker of atrial electrophysiological status. Work in progress aims to determine whether this new technique can aid selection of patients that are most likely to benefit from cardioversion. If the scalogram derived from wavelet analysis is shown to reflect the electrical status of the right atrium, providing information about the regularity and frequency of atrial re-entry circuits, then wavelet analysis may in future provide a useful non-invasive research tool for examining the effects of interventions (e.g. antiarrhythmic drugs) in patients with AF.

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